STABILITY AND ERROR ANALYSIS FOR ABSOLUTELY CALIBRATED GEODETIC GPS RECEIVERS

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Abstract

The absence of absolute calibration data for geodetic-quality Global Positioning System (GPS) receivers and their associated equipment has limited the application of these instruments for time transfer. We have conducted a series of tests in order to calibrate two such geodetic receivers. Receiver calibration is made with respect to a dual-frequency GPS simulator. Inaccuracies due to the simulator itself are minimized by the calibration procedure. The antenna and associated cables are calibrated using a vector network analyzer. Incorporating this information, we are able to provide an error budget for the absolute delay of an entire GPS receiver site. Methods for reducing this error budget are proposed.

The absolute calibration results for one receiver are compared to the results from a similar calibration performed 1 year earlier. Calibration stability is found to be on the order of 1 nanosecond for pseudoranges transmitted on both of the GPS frequencies (1575.42 and 1227.6 MHz). Laboratory calibration values are compared to in situ measurements in two modes: two receivers running off one antenna with a common clock, and two receivers running off two separate antennas with a common clock. Agreement is within the expected uncertainties based on the error budget described above. Using baselines on the order of 1000 km, calibrated GPS Carrier-Phase time transfer results are then compared to calibrated GPS Common View and Two-Way Satellite Time Transfer results. Agreement is again observed within the expected uncertainties.

Calibration of the carrier-phase technique must also include errors due to modeling of the observations (e.g., satellite orbits, atmospheric propagation) that are beyond the scope of this paper.

INTRODUCTION

High-precision frequency transfer has been established with geodetic-quality carrier-phase Global Positioning System (GPS) receivers [**1,2**]. Time transfer, on the other hand, requires knowledge of the hardware delays at each site. If these delays are known, time transfer can be accomplished between the two sites within the accuracy of the delay calculation and estimation strategy.

GEODETIC GPS RECEIVER ABSOLUTE CALIBRATION

The general procedure to calibrate an Ashtech Z-XII3T GPS receiver by use of a GPS simulator has been established in previous work done at the Naval Research Laboratory and elsewhere [**3,4,5**]. Using the same procedure and the same receiver, calibration stability has been shown to be on the order of 1 ns for pseudoranges on both frequencies (Table 1). However, the data from year 2 were collected with greater attention to detail than the first year. For instance, measurements were repeated many times to arrive at proper values. This may mean that the actual calibration stability is slightly better than what is shown in the table. In this paper, the second year's calibration values were used for analysis of experimental data. Note that for the second year, the calibration was performed twice, and the results represent an average of the two separate calibrations.

Table 1: Comparison of receiver calibrations performed 1 year apart. Delays are listed for Tick-to-Phase values of zero. P1 is the precise pseudorange on GPS frequency f_1 (1557.42 MHz), P2 is the precise pseudorange on GPS frequency f_2 (1227.60 MHz), and P3 is the ionosphere-free precise pseudorange combination.

Range	Year 1	Year 2
P1	294.75 ns	294.80 ns
P2	306.80 ns	308.00 ns
P3	276.13 ns	274.55 ns

From this table we see that the calibration is in excellent agreement for pseudorange P1. Taken exactly as shown, the stability of the receiver calibration for the ionosphere free combination is on the order of 1.5 ns. This is almost entirely due to the difference in the P2 calibration value. The difference in these calibration values is very close to the error budget, which we develop in the following section.

RECEIVER CALIBRATION ERROR BUDGET

In calculating the delay of the GPS receiver, several different measurements are required [**1,2**]. When possible, error estimates have been determined by taking several measurements and computing a standard deviation. Two measurements contributing to the uncertainty of the calibration are the Tick-to-Phase and Tick-to-Code delays, which are described in [**2**]. Briefly, the Tick-to-Phase measures the delay between the rising 1 Pulse Per Second (1 PPS) and the next rising zero of the external 20 MHz signal, while the Tick-to-Code measures the delay between the rising 1 PPS signal and the transition of the simulated pseudorange code.

Two other important error sources involve measuring connector delays. In order to measure the Tick-to-Code, the simulated GPS signal must be observed on a fast digital oscilloscope. This requires a connector that will not be in the signal path when the signal is injected into the receiver. Furthermore, the power level of the simulated signal must be amplified in order to be observed on the oscilloscope. RF pads must be placed inline to remove this amplification before the calibration can be performed. A DC block must also be placed inline with the receiver to prevent the receiver's antenna voltage from interfering with upstream equipment. In summary, the delays of the RF pads, the oscilloscope connectors, and the DC block must all be known in order to determine the true receiver delay.

While each of these components individually constitutes a delay that is a fraction of a nanosecond, the combined uncertainty increases the error budget. Error estimates for these measurements are detailed in Table 2.

The measurement of the Tick-to-Code serves as a simulator calibration [**3,4**]. However, in order to calculate the receiver delay, we rely on the simulator's output truth ranges to be accurate. The actual accuracy of these ranges is unknown. A conservative estimate places the simulator accuracy at 1 ns.

The Tick-to-Phase must be shifted several times in order to perform the calibration. A function generator is used to shift the phase of the 20 MHz external clock by 10 ns (72 degrees) at a time. The accuracy of these shifts is determined to be approximately 0.2 ns from the standard deviation of the resulting calibration curve.

Table 2: Single-frequency measurement errors for receiver calibration.

Error Source	Error Estimate
Tick-to-Phase	0.2 ns
Tick-to-Code	0.2 ns
Delay in RF pads	0.1 ns
Delay in connectors	0.1 ns
Delay in DC block	0.1 ns
Simulator Accuracy	1.0 ns
Function Generator	0.2 ns
$\sqrt{\Sigma\epsilon_i^2}$	1.1 ns

Combining these errors,

$$\varepsilon_{receiver} = \sqrt{\Sigma{\varepsilon_i}^2} = 1.1\,ns.$$

It is important to realize that the result above is the measurement error of either the P1 or P2 delay. To find the delay for the ionosphere-free combination P3, we must use the appropriate equation:

$$P3 \approx 2.545 * P1 - 1.545 * P2.$$

Therefore, the 1 sigma error on P3 becomes:

$$\varepsilon_{P3} = \sqrt{(2.545 * \varepsilon_{P1})^2 + (1.545 * \varepsilon_{P2})^2} = \sqrt{(2.545 * 1.1\,ns)^2 + (1.545 * 1.1\,ns)^2} = 3.3\,ns.$$

Therefore, since the ionosphere-free combination will be used for absolute time transfer, the calibration error for the receiver is 3.3 ns.

ANTENNA CALIBRATION

Calibrations of the antenna and antenna cable were performed in order to develop an accurate error budget for the entire GPS receiver site (Antenna + Antenna Cable + Receiver). The cable's electrical length is easily measured with a vector network analyzer for frequencies f_1 and f_2 to an accuracy of 0.1 ns. The antenna calibration is more complicated. In order to determine the delay through the antenna for both GPS frequencies, an anechoic chamber was used in concert with a vector network analyzer and a separate radiating antenna (see Figure 1). The delay is measured in three separate steps.

In the first step, a flat metal sheet is placed in the anechoic chamber where the antenna will eventually rest. The goal is to measure the electrical length of cable A, plus the radiating antenna, plus the air in the chamber (length B). By measuring the reflected peak caused by the flat metal surface, the electrical length is established. In the second step, the electrical length of cable C from the antenna back to the vector network analyzer is measured. In the third step, we attach the antenna to cable C, place it inside the chamber, and supply power to it. This is done with a bias-tee inline and energized, since the antenna will need to be powered in order to measure its delay. The vector network analyzer is then used to measure the total delay through cable A, through the radiating antenna, through the air in the chamber, through the antenna being calibrated, and finally through cable C.

The antenna delay is then measured as follows:

$$Antenna\,Delay = Total\,Delay - (Cable\,A\ +\ radiating\,antenna\ +\ chamber) - Cable\,C$$

The errors in this measurement are summarized in Table 3. There is some concern that calibrating the antenna in this way does not properly account for the pseudorange delay, since the bandwidth of the pseudorange information is close to 20 MHz. A better antenna calibration method needs to be developed in order evaluate the extent of this error.

Table 3: Single-frequency measurement errors for antenna calibration.

Error Source	Error Estimate
Cable A/ Chamber	0.1ns
Cable C	0.1 ns
Total Delay	0.1 ns
$\sqrt{\Sigma\epsilon_i^2}$	0.2 ns

$$\varepsilon_{antenna} = \sqrt{\Sigma\varepsilon_i{}^2} = 0.2\,ns.$$

This value of 0.2 ns is the error in the measurement of the antenna delay on f_1 or f_2. As before, the ionosphere free combination error becomes:

$$\varepsilon_{P3} = \sqrt{(2.545 * \varepsilon_{P1})^2 + (1.545 * \varepsilon_{P2})^2} = \sqrt{(2.545 * 0.2\,ns)^2 + (1.545 * 0.2\,ns)^2} = 0.6\,ns$$

Note that this antenna calibration is only for measurements from a 90-degree elevation angle (directly overhead). Phase center variations are not accounted for in this calibration and are beyond the scope of this paper [**6**].

TOTAL GPS SITE ERROR BUDGET

Combining the results from above, we list the total error budget for a GPS site in Table 4. For completeness, we must also include two more measurements. The accuracy of the 1 PPS (the "Tick") link from the clock to the receiver is also a factor in the overall time transfer that is not frequency-dependent. This value should be known to the accuracy of a cable measurement, which we take to be 0.1 ns. The Tick-to-Phase measurement must be taken to determine the calibration value. As before, the Tick-to-Phase can be measured within an uncertainty of 0.2 ns.

The overall accuracy of the absolute calibration is therefore known to within 3.4 ns. The dominant term in this calibration is the unknown accuracy of the simulator. If the simulator error is reduced to a mere 0.5 ns, the calibration accuracy would drop to 2.1 ns. If the simulator error is taken to be zero, then the calibration accuracy becomes 1.5 ns. For comparisons of receivers calibrated with the same simulator, it is entirely possible that the "relative" simulator error is much less than the stated 1 ns.

Table 4: Errors for calibration of entire GPS site.

Error Source	Error Estimate, single frequency	Error Estimate, ionosphere-free
Antenna	0.2 ns	0.6 ns
Antenna Cable	0.1 ns	0.3 ns
Receiver	1.1 ns	3.3 ns
Tick-to-Phase	0.2 ns	0.6 ns
1 PPS link	0.1 ns	0.3 ns
$\sqrt{\Sigma\epsilon_i^2}$	1.1 ns	3.4 ns

ZERO-BASELINE EXPERIMENT

Using two calibrated receivers, we then compare the predicted and observed results using the setup shown in Figure 2. The same clock is input to both receivers. In this experiment, a rubidium cell provided both a 10 MHz and 1 PPS output. The 10 MHz output was then converted to a 20 MHz signal by use of a function generator. Since the input clocks are identical, the difference in the receiver clock estimates is expected to be a constant. This constant should match the difference in the calibrated delays for each receiver. In this case, we are using a single antenna that is fed into a low-noise amplifier (LNA) followed by a splitter. The split signal is sent to each receiver via a short cable and RF attenuating pads. A DC block is used on each antenna as well, with antenna power being supplied via a bias tee upstream of the splitter. The amplifier and pads are essential to prevent coherent interference from signal reflections off of the splitter and amplifier. Several attempts at running this experiment failed until the RF pads and LNA were properly chosen and installed.

In a zero-baseline experiment, any component upstream of the splitter provides a common delay to both receivers. Therefore, the only delays that need to be accounted for are the splitter, the path from the splitter to the receive, and the receiver itself. The splitter, cables, RF pads, and DC blocks were chosen to be closely matched. A good conservative estimate for the difference in the path lengths is 0.3 ns.

In this experiment, the two receivers are designated DWH and CU. Table 5 shows the calibration results, adjusted for the measured Tick-to-Phase values, that were used to calculate the expected delays. Tick-to-Phase values were 12.2 ns for DWH and 14.5 ns for CU.

Table 5: Calibration differences for the zero-baseline experiment.

Observation	DWH delay	CU delay	Predicted Δ	Observed Δ	Difference
P1	278.0 ns	280.3 ns	-2.3 ns	-3.06 ns	-0.76 ns
P2	292.2 ns	293.5 ns	-1.3 ns	-2.47 ns	-1.17 ns
P3	256.1 ns	259.9 ns	-3.8 ns	-3.97 ns	-0.17 ns

To compute the solution, the observable equations are modeled using the GIPSY-OASIS software [**7**]. The analysis strategy is similar to that described by Larson and Levine [**1**]. The solution is computed every 5 minutes. After this analysis, the clock estimate (DWH-CU) is -3.97 ns. Accounting for calibration value of -3.8 ns from Table 5, the difference in the two clocks is observed to be -0.17 ns. The expected value is 0 ns, since the clocks are identical. These results are graphed in Figure 3. For a zero baseline, many error sources are identical for each receiver and, therefore, cancel out in the clock solutions. For example, the multipath signature will completely cancel out for each receiver. Delays due to the troposphere are also identical. Therefore, we expect that analysis of a zero-baseline clock experiment will result in the most precise solution possible, given the equipment setup. In this case, the standard deviation of the clock solution over 3 days is a mere 3 picoseconds. We expect the precision (and accuracy) of solutions will get worse as separate antennas and longer baselines are introduced.

SHORT-BASELINE EXPERIMENT

Following the success of the zero-baseline experiment, a short-baseline experiment was conducted. Once again, the same clock is input into both receivers, so the actual difference in clock solutions should be a constant. The setup used is shown in Figure 4. Identical Ashtech choke-ring antennas were placed approximately 1 meter apart. Two cables were used for each antenna: a 15-m Andrews Corporation Heliax phase-stabilized cable (FSJ1-50A) connected to 10 meters of shielded coaxial cable. The 10-m cables were not identical. One cable was Intercomp RG 214/U, while the other was Suprenant Wire & Cable MIL-C-17F. The differences in these two cables will be accounted for by switching them and observing the change in the time transfer solution. Antenna delays were assumed to be identical within measured uncertainties. However, this assumption must be questioned, and it may add 2-3 ns of uncertainty to the result.

At the end of the short-baseline experiment, the two 10-meter cables were switched and the experiment continued for approximately 3.5 hours. We expected the difference in shifting the cables to only be on the order of one nanosecond or less. Post-experiment analysis, however, revealed that swapping the cables caused a shift in the clock solution by approximately 12.1 ns. This was far from any predicted results and could only be explained by a problem in the hardware. Close inspection revealed that a connector was very poorly attached to one end of the MIL-C-17F cable. We propose that this poor connection caused coherent interference in the cable, significantly corrupting the results. Small problems with connectors have been shown to cause much larger jumps in group delay than one would expect; this phenomenon is caused by coherent interference [**8**]. To confirm that the cable was the cause of the problem, a second cable-swapping experiment was performed: the cables were started in the same original configuration for 6 hours, then swapped for 14 hours, and then returned to the original configuration for about 2 hours. The results were consistent with the first cable swap. Taking the mean of the clock estimates for each phase of the experiment, the average of the three clock differences is 12.0 ± 0.2 ns. Therefore, we conclude that the poor cable connection contributes an extra 6.0 ± 0.1 ns in delay to the clock estimates. Taking this value into account, we recalculate the clock estimates for the short-baseline experiment. Results are shown in Figure 5. Once again, a least-squares estimation of the clock solutions was generated by using GIPSY-OASIS software. Calibration delays have also been removed. The standard deviation of the solution is 29 ps, one order of magnitude greater than the standard deviation of the zero-baseline experiment. The solution's accuracy is well within the stated uncertainty.

COMPARISON WITH COMMON VIEW

GPS Common View (GPS CV) data are readily available to compare UTC(NIST) and UTC (USNO). UTC (USNO) is produced by Master Clock #2 (MC2). The GPS site at the United States Naval Observatory that is most reliable is connected to Master Clock #3 (MC3). This site, which is labeled as USNO in the IGS network, has not been calibrated. A second Ashtech Z-XII3T at the Naval Observatory has been calibrated and connected to MC2. However, this receiver, designated USN1, has been beset with problems due to failing equipment and difficulties in recording 1 Hz data. In the future, the USN1 receiver will provide a calibrated link to UTC (USNO). For the present, a link to UTC (USNO) must be found by other means. An experimental link between MC2 and MC3 calculates the difference in the two clocks every hour. This link is not temperature-stabilized [**9**]. The difference between the two clocks is routinely within ± 1 nanosecond, with a standard deviation of about 0.2 ns. Using data from this link on a day when USN1 had few data outages, the relative calibration of the two receivers at USNO was able to be determined. This relative calibration, combined with the updated hourly link data, allows UTC (NIST) to be compared with UTC (USNO) via GPS Carrier Phase (GPS CP). Because GPS CP solutions are produced every 5 minutes, a cubic spline was used on the MC2 to MC3 link data to produce interpolated clock differences.

A comparison of GPS Common View and GPS Carrier Phase results is seen in Figure 6. GPS CP estimates are computed in 24-hour batches with no further modifications. It is immediately apparent that the two series are off by approximately a constant value. Also, there is a large transient in the GPS CP data from day 562-564; this was mostly due to a temperature excursion when the environmental chamber was shut off for approximately 2 days. Unknown problems coincident at USNO also contribute to this error. The mean residual between the two series (GPS CP - GPS CV) is 9.5 ns. Note that the error in comparing two calibrated systems, without regard to the errors in the MC2 - MC3 link, is

$$\sqrt{2} * \varepsilon_{site} = \sqrt{2} * 3.4\,ns = 4.8\,ns.$$

The uncertainty in the accuracy of the GPS CV calibration, which should also be taken into account, is at least 5 ns and may be larger than 14 ns, based on the differences between Common View and Two-Way Satellite Time Transfer data published by the Bureau International des Poids et Mesures (BIPM) [**10,11**]. Therefore, the difference between the two time series is within the expected error for the GPS CP comparison. It should also be noted that the values from the Common View data fall below the BIPM circular T values, while the GPS Carrier Phase data fall above these values [**8**].

COMPARISON WITH CALIBRATED TWO-WAY SATELLITE TIME TRANSFER

A calibrated Two-Way Satellite Time Transfer (TWSTT) link is in constant operation between USNO and the Alternate Master Clock (AMC) in Colorado Springs, Colorado. The Alternate Master Clock is connected to a calibrated Ashtech Z-XII3T GPS site. Therefore, a comparison of TWSTT and GPS CP estimates is possible between these two sites. Once again, the process of linking GPS CP solutions to UTC (USNO) involves interpolating the experimental MC2-MC3 link at USNO, and calibration values obtained from the use of USN1. The overall accuracy of the TWSTT link is on the order of 1 nanosecond, subject to equipment failures [**9**]. Solutions are compared in Figure 7. Anomalies between days 561 and 565 are mostly due to an unknown problem with the USNO site over those days.

There are clearly problems with the Two-Way data for approximately 2 weeks prior to day 535. Only data since that date have been shown. The average residual TWSTT - GPS CP is 2.3 ns, well within the uncertainties of the calibrations.

ERROR REDUCTION IN FUTURE CALIBRATIONS

A better method of calibrating an Ashtech Z-XII3T would be to calibrate the entire system at once: antennna, cable, and receiver. This would be done using an anechoic chamber. If this could be accomplished, the errors due to RF pads, the DC block, and other connections would be virtually eliminated. Furthermore, this would allow for actual pseudorange delay calibration of the antenna, not just the delays at the carrier frequency. Since the simulated signal would pass through the antenna, the major obstacle to this proposed method would be correctly determining the Tick-to-Code. Currently, the Tick-to-Code measurement requires amplifying the simulated signal until it can be seen on an oscilloscope. The signal is returned to a more realistic level by use of attenuating pads. Using an amplifier and attenuating pads inline between the antenna and the receiver may allow for better antenna calibration, but the problem with the connectors would then remain.

CONCLUSION

With proper calibrations and equipment controls, GPS Carrier Phase is a reliable method for time transfer. Long-term stability of receiver calibrations is on the order of 1 nanosecond over 1 year. The accuracy of this time transfer method is better than that of GPS Common View methods. It also appears to be on par with the equipment intensive Two-Way Satellite Time Transfer method, but more study of this is warranted. More accurate calibration methods, as well as better estimation strategies, should further reduce the errors in this time transfer method.

ACKNOWLEDGMENTS

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[11] 22nd BIPM TWSTFT Report, 13 September 2002.

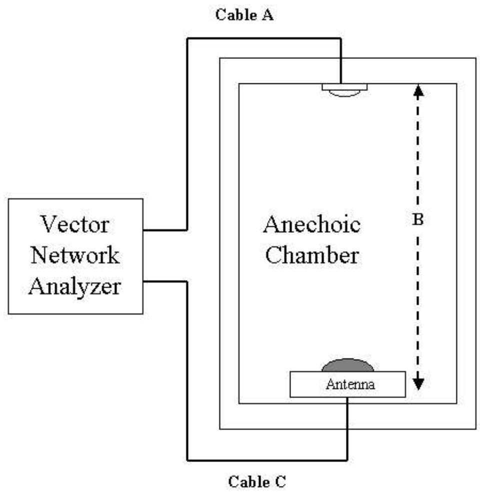

Figure 1: Antenna calibration setup.

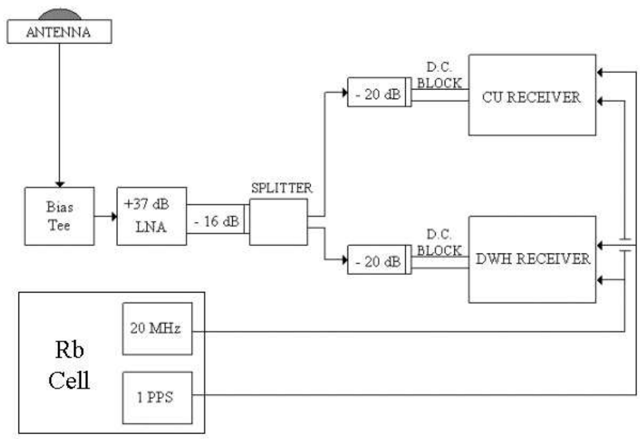

Figure 2: Zero-baseline experimental setup.

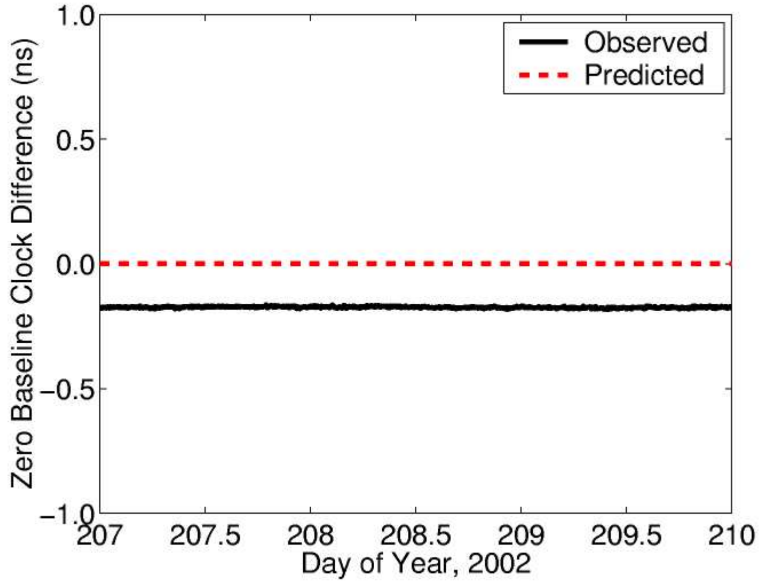

Figure 3: Comparison of observed and predicted differences in clock estimates for a zero-baseline experiment. The mean and standard deviation of the observed solution is -0.17 ns, and 0.003 ns, respectively.

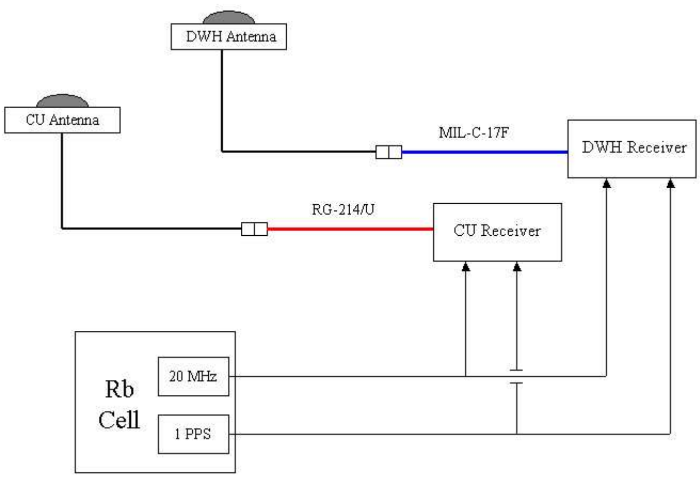

Figure 4: Short-baseline experimental setup.

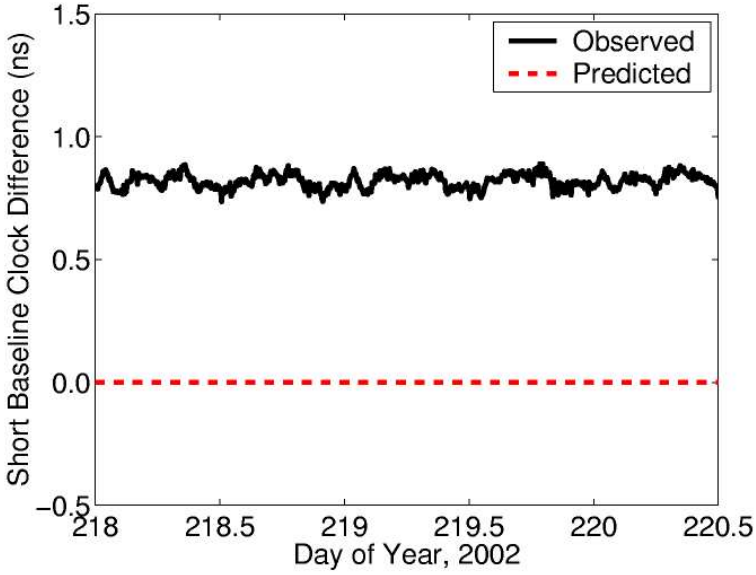

Figure 5: Comparison of observed and predicted differences in clock estimates for a short-baseline experiment. The mean and standard deviation of the observed solution is +.82 ns, and 0.029 ns, respectively.

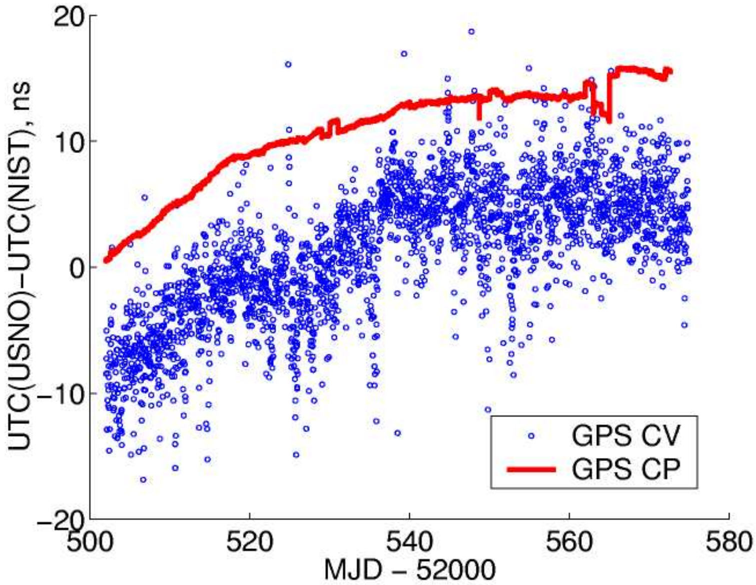

Figure 6: Comparison of GPS CV and GPS CP estimates of UTC(USNO)-UTC(NIST).

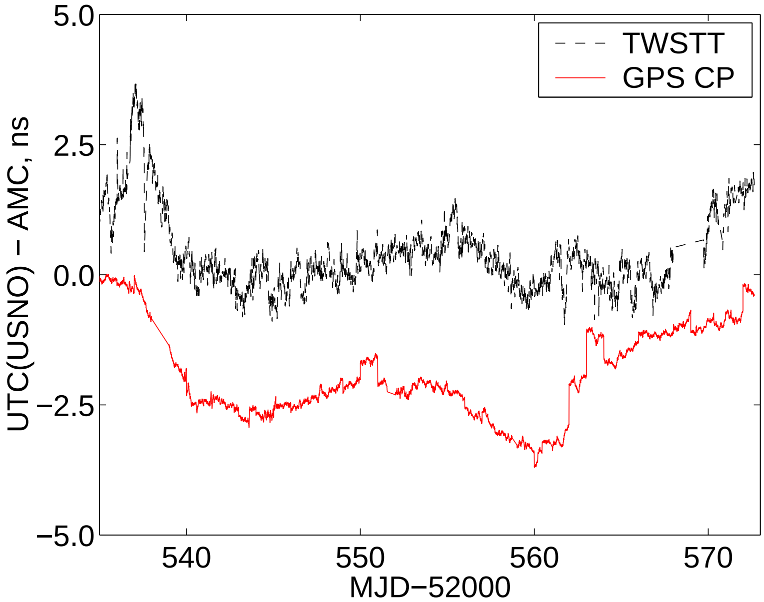

Figure 7: Comparison of TWSTFT and GPS CP estimates of UTC(USNO)-AMC.

QUESTIONS AND ANSWERS

KEN JOHNSTON (U.S. Naval Observatory): I will admit that it is probably more precise using this technique, but I am interested in accuracy in time transfer. In looking at your plots, which is the more accurate way? Or do they both have about the same accuracy in transferring time?

JOHN PLUMB: That is a tough question to answer, comparing to common view. So the question is which one of those is actually right? I think the calibrated link between the USNO and the Alternate Master Clock is pretty much acknowledged to be, I think, at the order of 1 nanosecond, somewhere in there. And so, for my results to be 2 nanoseconds away from that result tells me that that's about on par. When you look at the common view, we do not have a calibrated two-way link between the Observatory and NIST, so I don't have a good way to measure common view and that calibrated time transfer link, and GPS carrier phase to kind of see how the three of those play out against each other.

So my feeling is on par with two-way, and, of course, if you could calibrate receivers better, then I think it could be driven down farther.

KEN SENIOR (U.S. Naval Research Laboratory): I would like to just make a personal plug with respect to that question as well, directing you to the GPS World Innovation Column this month, wherein, albeit an internal measure of looking at what the capabilities are for carrier-phase time transfer, calibration issues aside, we use the day-boundary discontinuities, which, as you put it, you intend to fix. But the day-boundary discontinuities are also a very valuable measure with respect to the method, because they do give you at least an internal measure of how well you are doing timing-wise in the time transfer. And, in that paper, for example, we were able to share that if your receiver systems are very well controlled and you have got really good multi-path environment and so on, that the method gives repeatability within that internal measure at the level of about 120 picoseconds. Again, calibration issues aside. Just making a plug.

DEMETRIOS MATSAKIS (U.S. Naval Observatory): This will probably all come out in subsequent talks in this session. There is another technique, of course, and speaking to Ken's comment, which is looking at the residuals of the code solution. You gave a paper at the last PTTI, as did I, showing how that could be useful. But I really wanted to talk about which is more accurate and say that it is an entirely open question and maybe the wrong time to ask. Because both techniques, particularly two-way, are being improved considerably. The two-way system could be improved by a quantum leap in terms of precision when we go to carrier-phase TWSTT.

And also, in terms of temperature stabilization, you will hear from Tom Parker's talk, two-way is a little bit behind the carrier phase; the two-way is being improved that way as well. So I could suggest we wait a year.

TOM CLARK (Syntonics): You commented on the stability over a year of the receivers. Did you similar tests on the antenna structure? I am particularly interested in the band-pass filters that are associated with the pre-amplifiers in the antenna, which I personally think are pretty ugly things.

PLUMB: No, I didn't. I don't have any results on that, Tom.

JIM DeYOUNG (U.S. Naval Research Laboratory): I just do not remember my MJDs. Do we know what the two-way modem was that was used during this period? I would guess that is one of the NRL-designed modems.

PLUMB: That is the last 90 days, basically, up to about November 1st, is what you are looking at there. So whatever the modem is, that has been in use with AMC for the last couple months.